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Approximate analytic solution for performances of wet fins with a polynomial relationship between humidity ratio and temperature

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ABSTRACT

It is well known from the psychrometric properties of humid air that a linear relationship between specific humidity and dry bulb temperature (DBT) never exists. However, to establish analytical models of the performance and optimization analysis of wet fins, a linear relationship instead of psychrometric variation has been adopted by many researchers. For betterment of results in comparison with the existing value, the present study establishes a new approximate analytical model with the selection of the cubic polynomial relationship between specific humidity and dry bulb temperature. In view of this, thermal analysis of wet fins of straight profile has been addressed. The temperature profile and performance parameters of fully wet fins have been evaluated by Adomian decomposition method (ADM). A new scheme is furnished to carryout the performance analysis of partially wet fins using ADM. A notable difference in results is found while the present result has been compared with that values obtained from the published linear models.

1. Introduction

Fins or extended surfaces are frequently employed to increase the air side heat transfer rate in various heat exchange applications. Finned heat exchangers are commonly found in air conditioning, refrigeration, and process heat transfer where the temperature of the fin is lower than the dewpoint of the surrounding humid air as a result moisture in the air is condensed on the fin surface and, thus, the mass transfer takes place simultaneously with the heat transfer. Depending upon the fin surface temperature and dew-point of the surrounding air, heat transfer between the surrounding and the fin surface occurs all over the exposed surfaces in the form of either sensible or both sensible and latent heat. The difference of temperatures between air and fin surface is the driving force for sensible heat transfer and the difference of humidity ratio between the air and the adjacent air on the fin surface is the driving force for mass transfer. The moisture condenses on the fin surface in film-wise, dropwise or mixed mode depending upon the condition of the surface. In general, a clean surface tends to promote filmwise condensation whereas a treated surface condensates dropwise. For all the cases, a condensing surface is covered with a thin layer of liquid as the condensation takes place continuously over the fin surface and the condensed liquid is removed from the fin surface by the motion generated from gravity. However, owing to the built up of very thin condensate film with the boundary layer in the dehumidification process, the resistance of heat transfer through the condensate film is negligibly small and, thus, it has been omitted by many researchers [1–6].

To develop a theoretical model for predicting the thermal performance of fins under dehumidifying conditions, extensive works have been devoted by many investigators. McQuiston [1] and Threlkeld [7] had initiated first for this establishment. From their studies, a contradictory result has been observed for the variation of relative humidity of air on the overall fin efficiency. The McQuiston model shows that the overall efficiency strongly depends on the relative humidity whereas Threlkelds model gives less dependency upon the relative humidity. Elmahdy and Biggs [8] presented an algorithm to determine the efficiency of circular and longitudinal fins with a uniform thickness when simultaneous heat and mass transfer occur. The temperature distribution over the fin surface and the overall fin efficiency of a wet surface have been evaluated numerically using temperature and specific humidity differences as the motive forces for heat and mass transfer, respectively. Recently Sharqawy and Zubair [9] have established a numerical model for the efficiency of a straight rectangular fin under both completely wet and partially wet conditions by using the temperature and humidity ratio differences as the driving forces for heat and mass transfer. In their work, the actual

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Nomenclatures

A_j, B_j	Adomian's polynomials
ADM	Adomian decomposition method
Bi	Biot number, ht/k
c	dimensionless temperature gradient at the section where dry and wet part coexist
C_0, C_1, C_2, C_3	constants, defined in Eq. (7)
$C_{P,\ a}$	constant pressure specific heat for dry air, J kg^{-1} K^{-1}
$C(i,j)$	coefficient used in Eq. (26)
DBT	dry bulb temperature,°C
d_1,d_2,d_3	notations defined in Eq. (34)
f, g	functions defined in Eq. (21)
F_0,F_1,F_2,F_3	dimensionless parameters defined in Eq. (10)
h	convective heat transfer coefficient, W m^{-2} K^{-1}
h_{fg}	latent heat of condensation of moisture, J kg^{-1}
h_m	mass transfer coefficient, kg m^{-2} s^{-1}
J's	variables defined in Eq. (37)
K	thermal conductivity of the fin material, W m^{-1} K^{-1}
L	fin length, m
L	second order derivative
Le	Lewis number
n	number of terms considered
q	actual heat transfer rate per unit width, W m^{-1}
Q	dimensionless actual heat transfer rate, $q/[2k(T_a - T_b)]$
q_i	ideal heat transfer rate per unit width, W m^{-1}
Q_i	dimensionless ideal heat transfer rate, $q_i/[2k(T_a - T_b)]$
t	semi-fin thickness, m
T	local fin surface temperature,°C
T_a	ambient temperature,°C
T_b	base temperature,°C
T_d	dewpoint temperature,°C
x	coordinate as shown in Fig. 1, m
X	dimensionless coordinate, x/l
x_0	length of the dry region for a partially wet fin as shown in Fig. 1, m
X_0	dimensionless length of the dry region, x_0/l
Z_0	fin parameter, $\sqrt{Bi}/\psi$

Greek Letters

ϵ	fin effectiveness
ϕ	relative humidity of surrounding air
η	fin efficiency
θ	dimensionless local fin surface temperature, $(T_a - T)/(T_a - T_b)$
θ_0	dimensionless parameter defined in Eq. (24)
θ_d	dimensionless dewpoint temperature, $(T_a - T_d)/(T_a - T_b)$
ω	specific humidity, kg of water vapor per kg of dry air
ω_a	specific humidity of surrounding air, kg of water vapor per kg of dry air
ξ	dehumidification parameter, $h_{fg}/(C_{p,\ a}\mathrm{Le}^{2/3})$,°C
ψ	dimensionless thickness, t/L

psychrometric variation was considered for the relationship between the humidity ratio and temperature. A comparison of rectangular and triangular fins has been made by Toner et al. [10] when condensation occurs. A generalization technique was adopted to estimate the temperature profile as well as heat transfer rate. For the vertical fin of rectangular profile subject to both sensible and latent heat transfer, an approximate analytical solution has been demonstrated by Kilic and Onat [4] to determine the temperature in the fin using quasilinearization technique.

Elmahdy and Biggs [8] were the first researchers to introduce a linear relation between specific humidity of saturated air and fin surface temperature for performing numerical integration of the governing equation to estimate the temperature profile over the fin surface. Wu and Bong [2] have developed an exact analytical model for solving a governing differential equation for temperature distribution and overall fin efficiency of straight wet fins with the same assumption followed by Elmahdy and Biggs [8]. Later with satisfying this assumption, several research works [5,6,11–14] have been engaged in the estimation of analytical results for the wet fin efficiency of different geometries. In this standpoint, it is worthy to mention that according to the psychrometric chart for the saturated humid air, the relationship between specific humidity and dry bulb temperature (DBT) is curvilinear in nature and, consequently, its gradient varies with the DBT. Thus a linear nature of this gradient may be a crude approximation for the solution and perhaps it is applicable only for a differential range of temperature variation from fin base to fin tip. However in actual applications, it does not ever satisfy this differential range of temperature. Therefore for the accurate analysis of wet fins, it is obvious to consider the exact variation of specific humidity with the DBT instead of a linear variant.

For the detailed evaluation of the wet fin efficiency, Chen [15] had proposed a two-dimensional model taking into account of the complex fin geometry and a quadratic relation between specific humidity and temperature. Liang et al. [16] have introduced a polynomial variation of specific humidity with the fin surface temperature to establish a distributed simulation model for predicting steady state performance of a direct expansion air-cooling coil. A numerical method was used to calculate the partially wet and fully wet fin efficiency by taking into account of the refrigerant pressure drop along the coil. Coney et al. [17] used a second order polynomial that fits the saturation line in the psychrometric chart sufficiently well in the region of the fin temperature variation. Lin and Jung [18] have introduced a polynomial variation of specific humidity with the fin surface temperature to determine numerically two-dimensional fin efficiency of an elliptic fin under the dry, partially wet and fully wet conditions. By the regression analysis, this relationship has been derived into a second order polynomial equation.

The Adomian decomposition method (ADM) [19] has been successfully applied nowadays for solving a wide range of physical problems for mathematical models involving algebraic, differential, integro-differential and partial differential equations. This method provides a direct scheme for solving linear and nonlinear deterministic and stochastic equations without the need for linearization and yields rapidly convergent series solutions. To analyze the performance of longitudinal fin with constant heat transfer coefficient and variable thermal conductivity, Chiu and Chen [20] have applied this method. Kim and Huang [21] have given a recursive algorithm based on the Taylor series solution to solve fin problems with temperature-dependent thermal conductivity. Lesnic and Heggs [22] have determined the temperature distribution within a single fin with a temperature-dependent heat transfer coefficient using the ADM. With the help of the same methodology, Lesnic [23] described a nonlinear steady state diffusion process governed by a power law differential equation. The application of ADM to the analysis of convective–radiative fins has been investigated by Chiu and Chen [24].

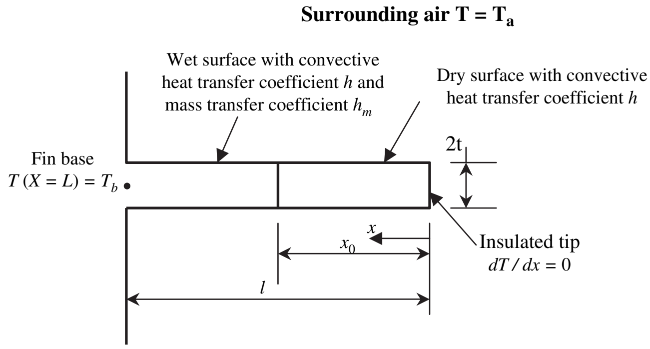

Fig. 1. Description of a one-dimensional partially wet fin.

The foregoing literature review summarized above shows that a thorough research work has been made on the fin problems subjected to combined heat and mass transfer conditions. To obtain an analytical solution of wet fins, many researchers [2,5,6,12–14] have assumed a linear relation of the saturation curves on the psychrometric chart. However, no work so far has been reported to analyze analytically the individual fins in wet conditions with consideration of the actual or psychrometric variation of specific humidity of air with the saturation temperature while the latent heat is calculated during dehumidification process. On the other hand, depending upon the thermophysical, geometric and psychrometric parameters of a design, fin surface becomes fully or partially wet. However, no analytical work has so far been engaged to analyze the partially wet fin with the consideration of the nonlinear variation of specific humidity with its temperature. These practical issues are motivated to carryout the present investigation.

In the present study, an approximate analytical ADM technique has been suggested to predict the overall fin performances of fully as well as partially wet fins by adopting a cubic polynomial relationship between specific humidity and fin surface temperature. To correlate the psychrometric relationship between specific humidity of saturated air and DBT, a cubic relation is considered because of the increase in accuracy level of result in comparison with that from the existing linear model. For the validation of the method, a numerical scheme has also been employed on the same problem. It is found from the result that the present analytical method is matched satisfactorily with that of the numerical technique. In order to provide the accuracy level of the present study, the outcomes from the present model have also been compared with those values obtained numerically by published model [9]. For a high value of relative humidity, a remarkable change on the temperature distribution between present and published results [6] has been noticed. However, it can be highlighted that the fin efficiency for fully wet fins depends marginally on the relative humidity whereas temperature distribution in the fin does have a relatively strong-function.

2. Statement of the problem and solution procedures

A straight fin with constant thermal conductivity k, unit width, constant thickness 2 t and length L is considered in the present study. A typical one-dimensional fin with the coordinate system is described in Fig. 1. The fin is attached to a primary surface of temperature T_b and extends into a surrounding air of dry bulb temperature T_a ($T_a > T_b$). The heat transferred from the surrounding air to the fin surface is occurred by convection and finally it is conducted through the fin. If the fin surface temperature is lower than the dewpoint temperature of the surrounding air, moisture is condensed on the fin surface by evolving the latent heat of condensation and, as a result, the fin surface becomes wet. Under this condition, mass transfer occurs simultaneously with the heat transfer on the fin surface. Depending upon the tip temperature, base temperature and dewpoint of the surrounding air, fin surface can be fully dry, partially wet or fully wet: for the fully wet surface, temperature of the fin tip is less than the dewpoint; a partially wet surface appears when the dewpoint temperature lies in between base and tip temperatures; dewpoint temperature is less than or equal to base temperature for the dry surface condition. For the development of the present theoretical model, isotropic fin material, constant convective heat transfer coefficient, and constant ambient and base temperatures are assumed. For the derivation of the energy equation in the wet fin, an incremental area is taken. Since the dehumidification of air on the fin surface takes place only when the fin surface temperature is less than the dewpoint of the surrounding air, it is, thus, necessary to govern, separately, the energy equation of fins for fully and partially wet surfaces. For the negligible heat transfer through the thickness-surfaces, the one-dimensional steady state heat balance equation for both the fully and partially wet conditions can be written as follows [2]:

Fully wet

$$d^2T/dx^2 = h\left\{ T - T_a + h_m(\omega - \omega_a)\, h_{fg}/h \right\}/(kt) \tag{1}$$

Partially wet

$$\begin{bmatrix} d^2T/dx^2 \\ d^2T/dx^2 \end{bmatrix} = \begin{bmatrix} h\left\{T - T_a + h_m(\omega - \omega_a)h_{fg}/h\right\}/(kt) \\ h(T - T_a)/(kt) \end{bmatrix} \begin{matrix} \text{for} x_0 \le x \le l \\ \text{for} 0 \le x \le x_0 \end{matrix} \tag{2}$$

where, x_0 is the length of the dry region for a partially wet surface. It is of interest to note that whether the surface is dry, fully or partially wet is only understandable after estimating the tip temperature. If the tip temperature is less than or equal to dewpoint of the surrounding air, the fin surface becomes fully wet ($x_0 = 0$). A partially wet surface is obtained when the dewpoint temperature is lower than the tip and higher than the base ($0 < x_0 < l$). From the Chilton–Colburn analogy [25] the heat and mass transfer coefficient can be correlated by a relation given below:

$$h/h_m = C_{p,\,a}\mathrm{Le}^{2/3} \tag{3}$$

By substituting Eq. (3), in Eqs. (1) and (2), it yields

Fully wet

$$d^2T/dx^2 = h\{T - T_a + \xi\,(\omega - \omega_a)\}/(kt) \tag{4}$$

Partially wet

$$\begin{bmatrix} d^2T/dx^2 \\ d^2T/dx^2 \end{bmatrix} = \begin{bmatrix} h\{T - T_a + \xi\,(\omega - \omega_a)\}/(kt) \\ h(T - T_a)/(kt) \end{bmatrix} \begin{matrix} x_0 \le x \le l \\ 0 \le x \le x_0 \end{matrix} \tag{5}$$

where

$$\xi = h_{fg}/\left(C_{p\,,\,a}\mathrm{Le}^{2/3}\right) \tag{6}$$

Equations (4) and (5) cannot be solved analytically because of two dependent variables T and ω unless one can be expressed as a function of the other. Thus using a correlation function, it is indispensable to convert to a single dependent variable. A large number of investigations have been attempted to carryout the wet-fin analysis with consideration of the specific humidity ratio ω as a linear function with T. However from the psychrometric chart, it is well known fact that the relation between ω and T of the saturated air is not linear in nature. However, very few studies of evaporator coil in humid environment have been analyzed numerically by choosing quadratic [15,17,18] and polynomial approximation of ω with T [16]. In the present study, a relation between ω and T is approximated by a cubic polynomial equation.

$$\omega = C_0 + C_1 T + C_2 T^2 + C_3 T^3 \tag{7}$$

where, the constants C_0, C_1, C_2 and C_3 are estimated, respectively, 3.7444×10^{-3}, 0.3078×10^{-3} (C^{-1}), $0.0046 \times 10^{-3}(C^{-2})$ and $0.0004 \times 10^{-3}(C^{-3})$ by regression analysis for the temperature range ($0\,^\circ\mathrm{C} \le T \le 30\,^\circ\mathrm{C}$). Equation (7) is formulated after satisfying the principle of minimization of error (less than 1%).

Using Eq. (7), Eqs. (4) and (5), the following equations in normalized form are obtained for the fully and partially wet surfaces:

Fully wet

$$\mathrm{d}^2\theta/\mathrm{d}X^2 = F_0 + F_1\theta + F_2\theta^2 + F_3\theta^3 \tag{8}$$

Partially wet

$$\begin{bmatrix} \mathrm{d}^2\theta/\mathrm{d}Z^2 \\ \mathrm{d}^2\theta/\mathrm{d}X^2 \end{bmatrix} = \begin{bmatrix} F_0 + F_1\theta + F_2\theta^2 + F_3\theta^3 \\ Z_0^2\theta \end{bmatrix} \quad \begin{matrix} (0 \le Z \le 1 - X_0) \\ (0 \le X \le X_0) \end{matrix} \tag{9}$$

where

$$\begin{bmatrix} F_0 \\ F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} Z_0^2\xi\left(\omega_a - C_0 - C_1T_a - C_2T_a^2 - C_3T_a^3\right)/(T_a - T_b) \\ Z_0^2\left[1 + \xi\left(C_1 + 2T_aC_2 + 3T_a^2C_3\right)\right] \\ -Z_0^2\,\xi\,(T_a - T_b)\,(C_2 + 3\,T_aC_3) \\ Z_0^2\,\xi\,C_3(T_a - T_b)^2 \end{bmatrix} \tag{10}$$

and

$$\begin{bmatrix} Z \\ Z_0 \\ \theta \end{bmatrix} = \begin{bmatrix} X - X_0 \\ \sqrt{Bi}/\psi \\ (T_a - T)/(T_a - T_b) \end{bmatrix} \tag{11}$$

Equations (8) and (9) are nonlinear second order ordinary differential equations and for their analytical solutions, it is always required a special technique. The ADM [19] is a method for solving a wide range of problems having nonlinearity terms in the governing equation. The governing fin equation is solved with satisfying Dirichlet and Neumann boundary conditions at the base and tip, respectively. In the case of partially wet fin the conditions at the common section where the dry and wet surfaces separate, are necessary for the establishment of the solution technique. To solve Eqs. (8) and (9), the following boundary conditions are employed:

$$\text{at}\ X = 0, \quad \mathrm{d}\theta/\mathrm{d}X = 0 \tag{12}$$

$$\text{at}\ X = X_0,\ [\mathrm{d}\theta/\mathrm{d}X]_{X=X_0} = [\mathrm{d}\theta/\mathrm{d}X]_{Z=0}\ \text{and}\ [\theta]_{X=X_0} = [\theta]_{Z=0} = \theta_d \tag{13}$$

$$\text{at}\ X = 1, \quad \theta = 1 \tag{14}$$

In this connection, it can be mentioned that for the fully wet fin, Eq. (8) is solved along with boundary conditions (12) and (14) only.

The ADM can provide analytical approximation to a rather wide class of nonlinear (and stochastic) equations without linearization, perturbation, closure approximations or discretization methods which can result in massive numerical computation. While the solution obtained by decomposition is generally an infinite series, an n-term approximation usually serves as a practical solution. However, the main advantage of decomposition method is that an accurate solution is often obtained with very small values of n. To establish the ADM for solving the present problem, the following mathematical steps are furnished.

The principle algorithm of ADM is demonstrated as follows:

$$L\theta = F_0 + F_1\theta + F_2\theta^2 + F_3\theta^3 \tag{15}$$

where, L is the taken as the highest order derivative (second order in the present study) to avoid difficult integration involving completed Green's functions. L is invertible and thus L^{-1} is regarded as the inverse operator of L and is defined by an indefinite integration from 0 to X and X_0 to X for the fully wet surface and the partially wet surface, respectively, i.e.

$$L^{-1}(\bullet) = \begin{cases} \int_0^X\int_0^X (\bullet)\,\mathrm{d}X\,\mathrm{d}X \ (0 \le X \le 1) & \text{for fully wet} \\ \int_0^X\int_0^X (\bullet)\,\mathrm{d}X\,\mathrm{d}X \ (0 \le X \le X_0) & \text{for partially wet} \\ \int_0^Z\int_0^Z (\bullet)\,\mathrm{d}Z\,\mathrm{d}Z \ (0 \le Z \le 1 - X_0) & \text{for partially wet} \end{cases} \tag{16}$$

As L is a second order operator L^{-1} is a two-fold indefinite integral.

$$L^{-1}L\theta = \begin{cases} \theta(X) - \theta(0) - X\mathrm{d}\theta(0)/\mathrm{d}X \ (0 \le X \le 1) & \text{fully wet} \\ \theta(X) - \theta(0) - X\mathrm{d}\theta(0)/\mathrm{d}X \ (0 \le X \le X_0) & \text{partially wet} \\ \theta(Z) - \theta(0) - Z\mathrm{d}\theta(0)/\mathrm{d}Z \ (0 \le Z \le 1 - X_0) & \text{partially wet} \end{cases} \tag{17}$$

Operating on both sides of Eq. (15) with L^{-1} yields

$$L^{-1}L\theta = \begin{cases} L^{-1}F_0 + L^{-1}(F_1\theta) + L^{-1}\left(F_2\theta^2\right) + L^{-1}\left(F_3\theta^3\right) & (0 \le X \le 1) & \text{fully wet} \\ L^{-1}\left(Z_0^2\theta\right) & (0 \le X \le X_0) & \text{partially wet} \\ L^{-1}F_0 + L^{-1}(F_1\theta) + L^{-1}\left(F_2\theta^2\right) + L^{-1}\left(F_3\theta^3\right) & (0 \le Z \le 1 - X_0) & \text{partially wet} \end{cases} \tag{18}$$

Combining Eqs. (17) and (18), yields

$$\theta = \begin{cases} \theta(0) + X\mathrm{d}\theta\,(0)/\mathrm{d}X + F_0X^2/2 + F_1L^{-1}\theta + F_2L^{-1}\theta^2 + F_3L^{-1}\theta^3 & (0 \le X \le 1) & \text{fully wet} \\ \theta(0) + X\mathrm{d}\theta\,(0)/\mathrm{d}X + Z_0^2L^{-1}\theta & (0 \le X \le X_0) & \text{partially wet} \\ \theta(0) + Z\mathrm{d}\theta\,(0)/\mathrm{d}Z + F_0Z^2/2 + F_1L^{-1}\theta + F_2L^{-1}\theta^2 + F_3L^{-1}\theta^3 & (0 \le Z \le 1 - X_0) & \text{partially wet} \end{cases} \tag{19}$$

The decomposition method represents the solution of Eq. (19) as an infinite series

$$\theta = \sum_{j=0}^{n} \theta_j \tag{20}$$

The terms θ^2 and θ^3 in Eq. (18) are nonlinear, they can be decomposed, respectively as

$$\begin{bmatrix} \theta^2 \\ \theta^3 \end{bmatrix} = \begin{bmatrix} \sum_{j=0}^{n} A_j \\ \sum_{j=0}^{n} B_j \end{bmatrix} = \begin{bmatrix} f(\theta) \\ g(\theta) \end{bmatrix} \tag{21}$$

Equation (19) can be expressed by using Eqs. (20) and (21) as

$$\begin{bmatrix} \sum_{j=0}^{n} \theta_j(X) \\ \sum_{j=0}^{n} \theta_j(X) \\ \sum_{j=0}^{n} \theta_j(Z) \end{bmatrix} = \begin{bmatrix} \theta_0 + F_1 L^{-1} \sum_{j=0}^{n-1} \theta_j + F_2 L^{-1} \sum_{j=0}^{n-1} A_j + F_3 L^{-1} \sum_{j=0}^{n-1} B_j \\ \theta_0 + Z_0^2\, L^{-1} \sum_{j=0}^{n-1} \theta_j \\ \theta_0 + F_1 L^{-1} \sum_{j=0}^{n-1} \theta_j + F_2 L^{-1} \sum_{j=0}^{n-1} A_j + F_3 L^{-1} \sum_{j=0}^{n-1} B_j \end{bmatrix} \begin{matrix} \text{fully wet}(\, 0 \le X \le 1\,) \\ \text{partially wet}(\, 0 \le X \le X_0) \\ \text{partially wet}(\, 0 \le Z \le 1 - X_0) \end{matrix} \tag{22}$$

where

$$\theta_0 = \begin{cases} \theta_t + X\mathrm{d}\theta(0)/\mathrm{d}X + F_0 X^2/2 & \text{fully wet}(\, 0 \le X \le 1\,) \\ \theta_t + X\mathrm{d}\theta(0)/\mathrm{d}X & \text{partially wet}(\, 0 \le X \le X_0) \\ \theta(0) + Z\mathrm{d}\theta\,(0)/\mathrm{d}Z + F_0 Z^2/2 & \text{partially wet}(\, 0 \le Z \le 1 - X_0) \end{cases} \tag{23}$$

The tip temperature $\theta(0)$ is denoted by θ_t. For the fully wet surface, the expression of θ_0 can be simplified by using tip boundary condition (Eq. (12)) and in the case of partially wet fin it can be expressed by satisfying the boundary conditions (Eqs. (12) and (13)) as

$$\theta_0 = \begin{cases} \theta_t + F_0 X^2/2 & \text{fully wet}(0 \le X \le 1) \\ \theta_t & \text{partially wet}(0 \le X \le X_0) \\ \theta_d + Z\mathrm{d}\theta\,(0)/\mathrm{d}Z + F_0 Z^2/2 & \text{partially wet}(0 \le Z \le 1 - X_0) \end{cases} \tag{24}$$

Consequently, Eq. (22) can be written as

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_{n+1} \end{bmatrix} = \begin{bmatrix} F_1 L^{-1}\theta_0 + F_2 L^{-1} A_0 + F_3 L^{-1} B_0 \\ F_1 L^{-1}\theta_1 + F_2 L^{-1} A_1 + F_3 L^{-1} B_1 \\ \vdots \\ F_1 L^{-1}\theta_n + F_2 L^{-1} A_n + F_3 L^{-1} B_n \end{bmatrix} \quad \text{for } n \ge 0 \tag{25}$$

$$\begin{bmatrix} A_4 \\ B_4 \end{bmatrix} = \begin{bmatrix} C(1,\ 4)f^{(1)}(\theta_0) + C(2,\ 4)f^{(2)}(\theta_0) \\ C(1,\ 4)g^{(1)}(\theta_0) + C(2,\ 4)g^{(2)}(\theta_0) + C(2,\ 5)g^{(2)}(\theta_0) + C(3,\ 2)g^{(3)}(\theta_0) \end{bmatrix} = \begin{bmatrix} 2\theta_0\,\theta_4 + \theta_2^2 + 2\theta_1\,\theta_3 \\ 3\theta_0^2\,\theta_4 + 3\theta_2^2\theta_0 + 3\theta_1^2\theta_2 + 6\theta_0\theta_1\theta_3 \end{bmatrix} \tag{32}$$

where A_n and B_n are Adomian polynomials depending on θ_0, θ_1,…, θ_n. All components are determinable since A_0 and B_0 depend on θ_0. A_1 and B_1 depend on θ_0, θ_1, etc. The practical solution will be the n-th term approximation. For the rapidity of convergence, few terms are required for the mathematical formulation. The polynomial A_j and B_j in Eq. (21) can be obtained by expanding the functions f and g in a generalized Taylor series expansion. Thus the Adomian polynomial are determined from the following formula:

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \begin{bmatrix} f(\theta_0) \\ g(\theta_0) \end{bmatrix} \text{and} \begin{bmatrix} A_i \\ B_i \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{i} C(j,i) f^{(j)}(\theta_0) \\ \sum_{j=1}^{i} C(j,i) g^{(j)}(\theta_0) \end{bmatrix} \ \text{for}\, i \ge 1 \tag{26}$$

and

$$\begin{bmatrix} f(\theta_0) \\ g(\theta_0) \end{bmatrix} = \begin{bmatrix} \theta_0^2 \\ \theta_0^3 \end{bmatrix} \tag{27}$$

the second index in the coefficient is the order of derivative and the first index progresses from 1 to i along with the order of the derivative. In Eq. (26), $C(j, i)$ are products of the j components of θ whose subscripts sum to i. Accordingly, the A_i's and B_i's can be expressed as

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \begin{bmatrix} f(\theta_0) \\ g(\theta_0) \end{bmatrix} = \begin{bmatrix} \theta_0^2 \\ \theta_0^3 \end{bmatrix} \tag{28}$$

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} C(1,\ 1)f^{(1)}(\theta_0) \\ C(1,\ 1)g^{(1)}(\theta_0) \end{bmatrix} = \begin{bmatrix} 2\theta_0\theta_1 \\ 3\theta_0^2\theta_1 \end{bmatrix} \tag{29}$$

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \begin{bmatrix} C(1,\ 2)f^{(1)}(\theta_0) + C(2,\ 2)f^{(2)}(\theta_0) \\ C(1,\ 2)g^{(1)}(\theta_0) + C(2,\ 2)g^{(2)}(\theta_0) \end{bmatrix} = \begin{bmatrix} 2\theta_0\,\theta_2 + \theta_1^2 \\ 3\theta_0^2\,\theta_2 + 3\theta_0\theta_1^2 \end{bmatrix} \tag{30}$$

$$\begin{bmatrix} A_3 \\ B_3 \end{bmatrix} = \begin{bmatrix} C(1,\ 3)f^{(1)}(\theta_0) + C(2,\ 3)f^{(2)}(\theta_0) \\ C(1,\ 3)g^{(1)}(\theta_0) + C(2,\ 3)g^{(2)}(\theta_0) + C(3,\ 1)g^{(3)}(\theta_0) \end{bmatrix} = \begin{bmatrix} 2\theta_0\,\theta_3 + 2\theta_1\theta_2 \\ 3\theta_0^2\,\theta_3 + 6\theta_0\theta_1\theta_2 + \theta_1^3 \end{bmatrix} \tag{31}$$

$$\vdots \quad = \quad \vdots$$

Now that the $\{A_j\}_{j=0}^{\infty}$ and $\{B_j\}_{j=0}^{\infty}$ are known, θ_i using Eq. (25) can be assigned and it is needed to impose the inverse operator L^{-1} on both sides. For the optimal convergence, they are to be taken in the following way. θ_i's for the fully and partially wet surfaces can be expressed in terms of θ_t and X_0 separately as

Fully wet

$$\begin{bmatrix}\theta_1\\ \theta_2\\ \\ \vdots\end{bmatrix}=\begin{bmatrix}\theta_t d_1X^2/2!+d_2F_0X^4/4!+6F_0^2d_3X^6/6!+90F_0^3F_3X^8/8!\\ \theta_t d_1d_2\,X^4/4!+F_0\left(d_2^2+12\theta_t d_1d_3\right)X^6/6!+18F_0^2(2d_2d_3+15\theta_t d_1F_0F_3)X^8/8!\\ +6F_0^3\left(56d_3^2+225F_3d_2\right)X^{10}/10!+30780d_3F_0^4F_3X^{12}/12!+801900F_0^5F_3^2X^{14}/14!\\ \vdots\end{bmatrix} \tag{33}$$

where

$$\begin{bmatrix}d_1\\ d_2\\ d_3\end{bmatrix}=\begin{bmatrix}F_1+F_2\theta_t+F_3\theta_t^2\\ F_1+2\theta_tF_2+3\theta_t^2F_3\\ (F_2+3\theta_tF_3)\end{bmatrix} \tag{34}$$

Partially wet

$$\begin{bmatrix}\theta_1\\ \theta_2\\ \theta_3\\ \vdots\end{bmatrix}=\begin{bmatrix}\theta_tZ_0^2X^2/2!\\ \theta_tZ_0^4X^4/4!\\ \theta_tZ_0^6X^6/6!\\ \vdots\end{bmatrix}\quad \text{for}(0\le X\le X_0) \tag{35}$$

$$\begin{bmatrix}\theta_1\\ \\ \theta_2\\ \\ \vdots\end{bmatrix}=\begin{bmatrix}\theta_dd_1\,Z^2/2!+cd_2\,Z^3/3!+(F_0d_2+2c^2d_3)Z^4/4!+6c(F_0d_3+c^2F_3)Z^5/5!\;+6F_0(F_0d_3+6c^2F_3)Z^6/6!\\ +90cF_0^2F_3Z^7/7!+90F_0^3F_3Z^8/8!\\ \theta_dd_1d_2Z^4/4!\;+c\left(d_2^2+6\theta_dd_1d_3\right)Z^5/5!\;+J_1Z^6/6!+cJ_2Z^7/7!+J_3Z^8/8!\;+cJ_4Z^9/9!+J_5Z^{10}/10!\\ +cJ_6Z^{11}/11!+F_0^3F_3(30780F_0d_3+354780F_3c^2)Z^{12}/12!\;+801900F_0^4F_3^2cZ^{13}/13!\;+801900F_0^5F_3^2Z^{14}/14!\\ \vdots\end{bmatrix}$$

$$\text{for}(0\le Z\le 1-X_0) \tag{36}$$

where

$$\begin{bmatrix}J_1\\ J_2\\ J_3\\ J_4\\ J_5\\ J_6\end{bmatrix}=\begin{bmatrix}F_0\left(d_2^2+12\theta_dd_1d_3\right)+2c^2(d_2d_3+4d_2d_3+18\theta_dd_1F_3)\\ 6F_0d_2d_3+66c^2F_3d_2+30d_2F_0F_2+20c^2d_3F_2+90\theta_dd_2F_0F_3+60\theta_dc^2d_3F_3+180\theta_dd_1F_0F_3\\ F_0^2(36d_2d_3+270\theta_dd_1F_3)+c^2\left(486d_2F_0F_3+132d_3^2F_0+252c^2d_3F_3\right)\\ 1350d_2F_0^2F_3+336d_3^2F_0^2+2772c^2d_3F_0F_3+756c^4F_3^2\\ F_0F_3\left(1350F_0^2d_2+336d_3^2F_0^2\right)+c^2F_0F_3(12024d_3F_0+2016F_0F_2+18144c^2F_3)\\ cF_0^2F_3(30780d_3F_0+68040c^2F_3)\end{bmatrix} \tag{37}$$

Now the $\{\theta_j\}_{j=0}^{\infty}$ are known, so the solution is given by

$$\theta=\begin{cases}\sum_{j=0}^{n}\theta_j\ \text{for}(0\le X\le 1) & \text{for fully wet}\\ \begin{cases}\theta_d\cosh(Z_0X)/\cosh(Z_0X_0)\ \text{for}(0\le X\le X_0)\\ \sum_{j=0}^{n}\theta_j\text{for}(X_0\le X\le 1)\end{cases} & \text{for partially wet}\end{cases} \tag{38}$$

The number of term 'n' is chosen in such a way that the final result from the above equation can be obtained with a desired accuracy (in the present study, 10^{-5} is taken). In this regards, it may be noted that the desired accuracy for the ADM solution is reached with a very small value of n. Here it can also be mentioned that the temperature distribution expressed in Eqs. (33), (35) and (36) is separately as a function of unknown tip temperature θ_t for the fully wet fin and as a function of unknown dry length $X_0$and $c[=(d\theta/dX)_{Z=0}]$for the partially wet fin. These two unknowns can be determined from the algorithm of Newton–Raphson iterative method [26] in satisfying the boundary condition at the fin base (Eq. (14)) and the section where dry and wet parts coexist (Eq. (13)). After getting the temperature distribution, the heat transfer rate can be calculated by applying the Fourier's law of heat conduction at the fin base and it can be expressed mathematically as

$$Q\;=\;q/[2\,k\,(T_a-T_b)\,]\;=\;\psi\sum_{j=0}^{n}[\,\mathrm{d}\theta_j/\mathrm{d}X]_{X=1} \tag{39}$$

The rate of heat that would be transferred if the entire fin surfaces were at base temperature. The calculation of ideal heat transfer rate for wet fins (fully or partially) is made with the consideration of a fully wet surface. Mathematically it is given by

$$\begin{aligned}Q_i&=q_i/[2k(T_a-T_b)]\\ &=\psi Z_0^2\left[1+\xi\left(\omega_a-C_0-C_1T_b-C_2T_b^2-C_3T_b^3\right)/(T_a-T_b)\right]\end{aligned} \tag{40}$$

Therefore, from definition of fin efficiency, it can be written as

$$\eta\;=\;Q/Q_i \tag{41}$$

The fin effectiveness is defined as the ratio of actual heat transfer rate to the rate of transfer of heat through the base surface if there was no fin. Thus the fin effectiveness can be expressed as

$$\epsilon = \left(\psi Z_0^2\right)^{-1} \sum_{j=0}^{n} \left[\mathrm{d}\theta_j/\mathrm{d}X\right]_{X=1} \Big/ \Big[1+\xi\Big(\omega_a - C_0 - C_1 T_b - C_2 T_b^2 - C_3 T_b^3\Big)/(T_a - T_b)\Big] \tag{42}$$

In this section, it may be noted that an analytical scheme has been demonstrated to estimate the fin performance of wet fin under both fully and partially wet conditions.

3. Results and discussion

Based on the above analysis, temperature distribution over the fin surface and the overall fin performances are estimated for a design condition of constant DBT, fin base temperature and relative humidity. As the above analysis has been presented as a function of specific humidity, it requires an intermediate psychrometric step to obtain the result with the variation of the above design variables. In order to make a comparison between the present and the published results as well as to provide a useful assessment of the accuracy of the present method, the results obtained from the present analysis are compared with that of the Wu and Bong [2] and Sharqawy and Zubair [6,9] models. According to the Wu and Bong linear model, specific humidity of air varies linearly with the corresponding local saturation temperature along the length of the fin. This linear nature is determined from the known psychrometric conditions at the base and tip. However, the psychrometric condition at the tip is dependent upon the tip temperature which is only known after solving the governing energy equation of a fin under fully wet condition. Hence an implicit relationship between psychrometric properties at the tip and tip temperature exists. To obtain the fin surface temperature for fully wet fins, iteration is required. To avoid this process, Sharqawy and Zubair [6] adopted a linear model by selecting the dewpoint temperature at the tip which is used for the calculation of the psychrometric properties of air only.

The numerical solution is obtained for the present problem by developing an algorithm where the domain is discretized by Taylor series central difference scheme using linearization of source term [27] and finally difference equations have been solved by Gauss–Seidel iterative method [26]. For taking the numerical result, grid independency test has been done. In order to fix up the nodal points used in the numerical calculation for tip temperature, 35, 50 and 100 meshes are tested for$Z_0 = 1$and $\phi = 100\%$. The relative error for calculating tip temperature is 0.078% when the number of meshes is increased from 35 to 50. The relative error is decreased to 0.002% when 50 meshes are doubled to 100. Hence 100 meshes have finally been adopted for numerical calculation. A numerical result is therefore computed for the present problem solving the difference equations at pivotal points by Gauss–Seidel iterative method with the imposition of the appropriate boundary conditions and the final result yields after satisfying the convergence criteria.

Fig. 2 depicts the temperature distribution in wet fins for different relative humidity of air and a design condition. It may be noted from the figure that the dimensionless temperature in wet fins decreases by increasing relative humidity which indicates an increase in dimensional fin surface temperature. It is an expected observation because of evolving of more latent heat of condensation on the fin surface due to increase in moisture content in the air with the increment of relative humidity. In comparison of accuracy level of different models existed in the literature, the result obtained from the Wu and Bong [2] and Sharqawy and Zubair [6,9] analyses has been plotted in the same figure. The numerical result for the same design condition is also drawn. The result obtained from the present model matches satisfactorily with the corresponding numerical values irrespective of relative humidities adopted whereas a difference in results is noticed when present

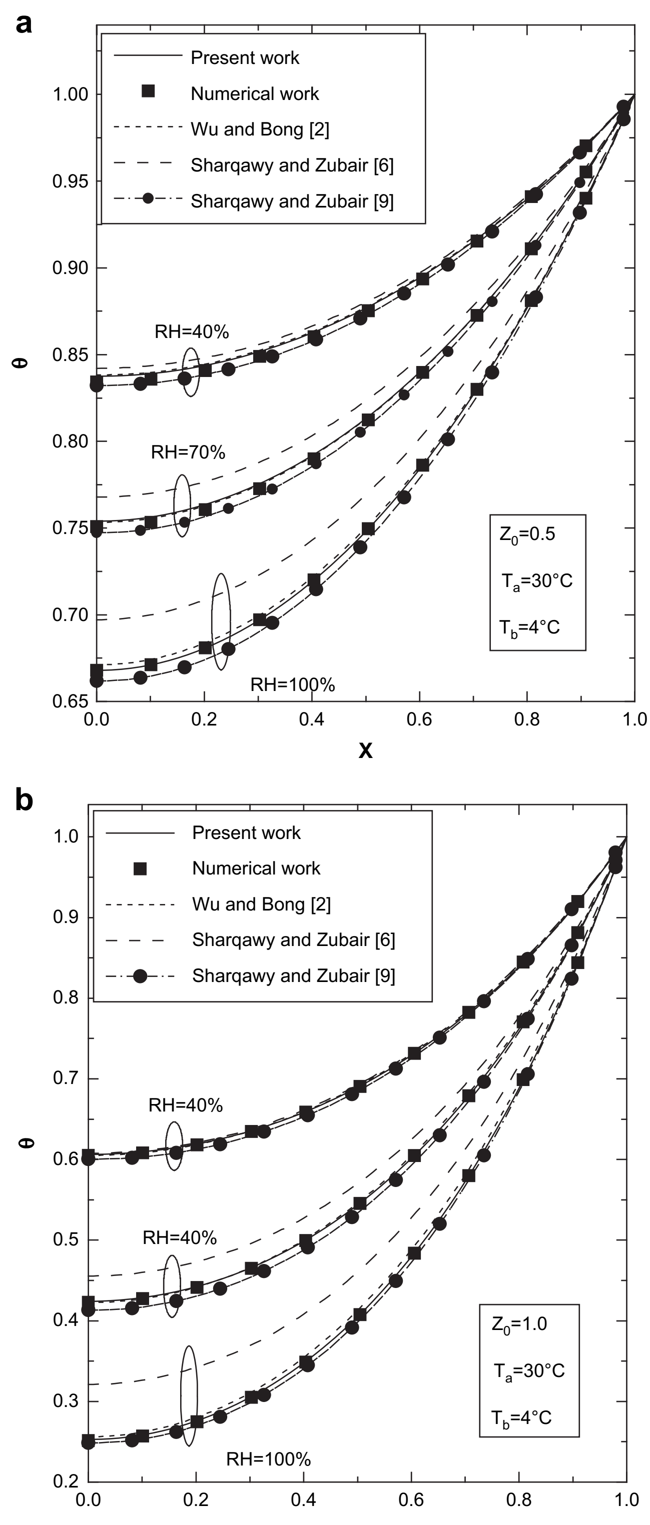

Fig. 2. Temperature distribution in wet fins for different relative humidity predicted by different methods: (a) $Z_0 = 0.5$; (b) $Z_0 = 1.0$.

work is compared with the published models at higher values of relative humidity. A notable difference in results is found when it's compared with the result from Sharqawy and Zubair [6] linear analysis. However, difference in results shows marginally when comparative study has been made between the present model and published numeric model [9]. The same nature in curves has also been found for other values of Z_0. However, increase in fin parameter Z_0 always increases the fin surface temperature which can be understandable by comparing Fig. 2a and 2b.

The effect of ambient temperature on the wet fin surface temperature is exhibited in Fig. 3 for different relative humidity conditions. With the increase in ambient temperature, fin surface temperature increases for a constant relative humidity. This is due to more condensation of moisture on the fin surface as the moisture content in the air is an incremental function with the ambient temperature for a constant relative humidity. This examination has also been done by other methods of prediction. Again the numerical prediction gives very closer to the present approximate analytical values for all different values of ambient and relative humidities. However, the accuracy level of matching is also dependent upon the fin parameter Z_0. Nevertheless, published linear model [2,6] predicts a difference in results with respect to the present result at a high value of relative humidity which is exhibited in Fig. 3. This difference in results does not depend significantly on the ambient temperature. Therefore, a caution has to be required for adopting a linear model to predict the temperature distribution in wet fins at high values of relative humidity of air. Especially a great attention is

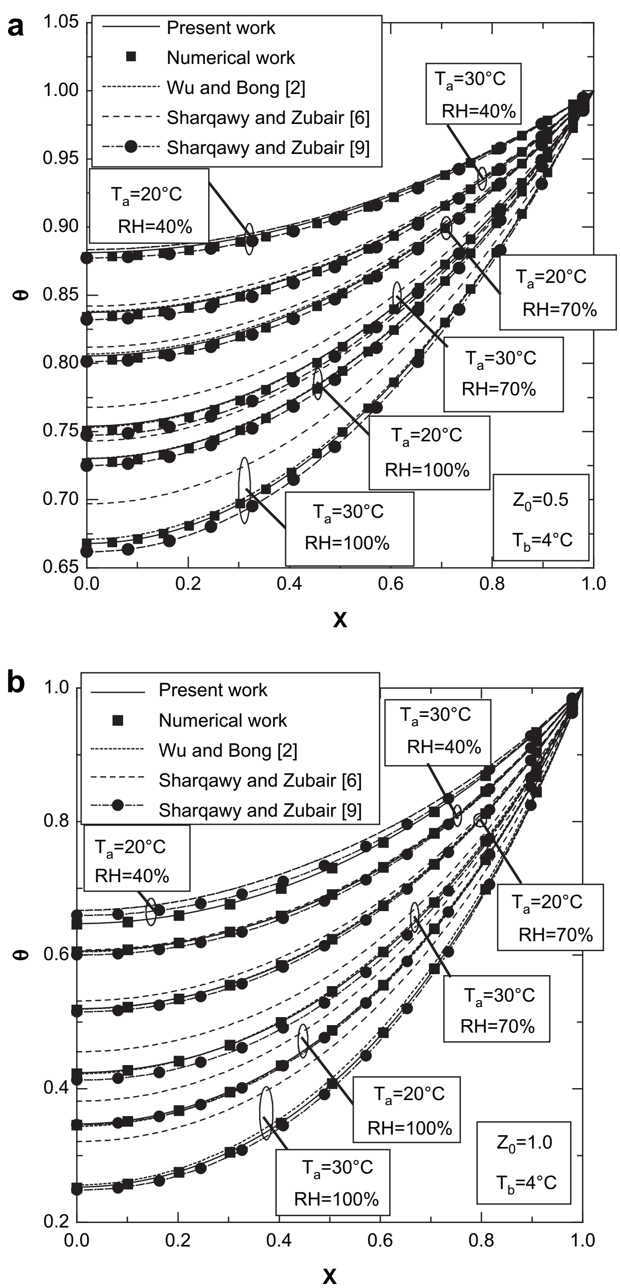

Fig. 3. The effect of relative humidity and temperature of surrounding air on the fin surface temperature predicted by different methods: (a) $Z_0 = 0.5$; (b) $Z_0 = 1.0$.

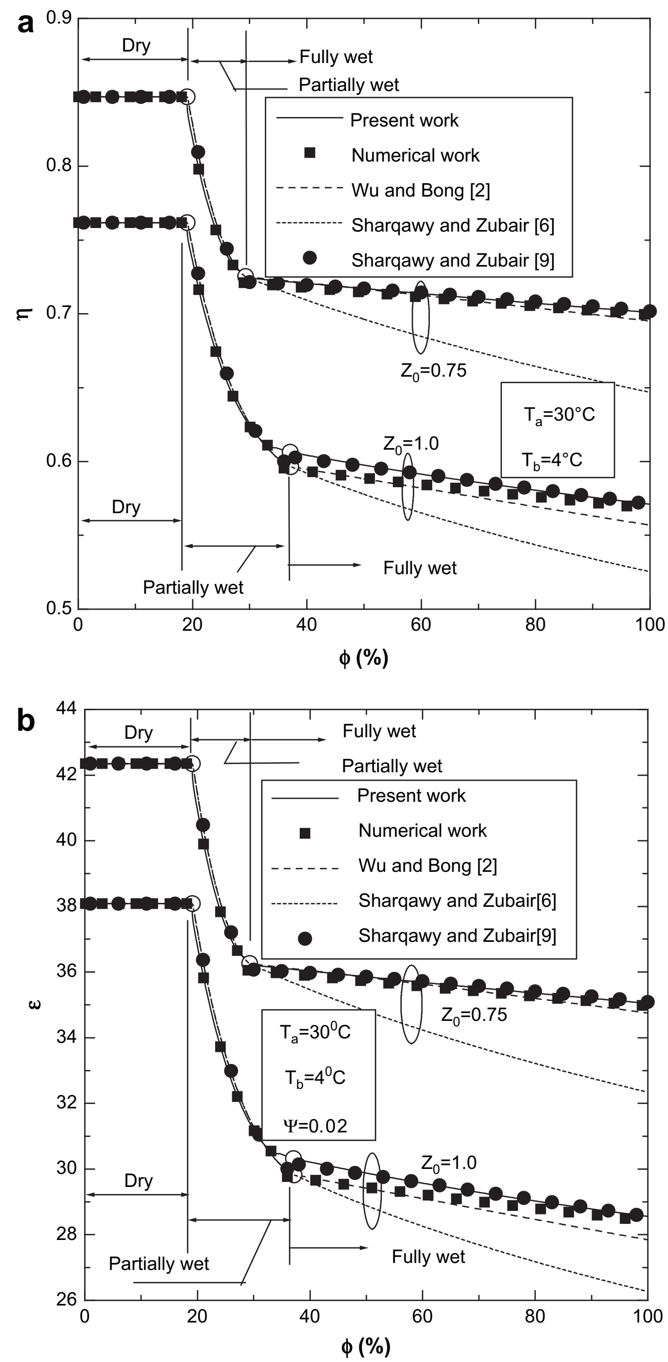

Fig. 4. Comparison of present and previous results of fin performances with variation of full range of relative humidity under the same design condition: (a) Fin efficiency; (b) Fin effectiveness.

necessary while prediction of fin temperature by selecting Sharqawy and Zubair linear model [6]. On the other hand, the present analytical model predicts a little difference in results from the published numerical values [9] and it is also dependent upon the psychrometric design conditions.

Next, based on the present analysis, fin performances have been determined for a wide range of thermo-psychrometric parameters. The one of the main objectives of the present study is to forecast errors associated with the published papers by consideration of a linear relation between specific humidity and film temperature on the fin surface. For this establishment, an exercise has been devoted to make a comparison of results for fin performances obtained from the numerical analysis, present model and published model [2,6,9]. This comparative study has been made with the help of Fig. 4 for the whole of range of relative humidity and different constant fin parameters, viz. $Z_0 = 0.75$ and $Z_0 = 1.0$. The fin performances, namely fin efficiency and fin effectiveness of wet fins decline with relative humidity. This effect is pronounced in partially wet fin in comparison with the fully wet condition. From the graph, it can be demonstrated that in a fully wet fin, the difference in results obtained from the present and published studies [2,6] gradually increases with the increase in relative humidity and this deviation becomes maximum at the relative humidity of 100%. However, there is no such large deviation is existed in a partially wet fin. It may further be noted that with the increase in relative humidity, the temperature on the fin surface increases due to production of more latent heat of moisture on the fin surface for a constant base and ambient temperatures. Finally, it can be concluded from the figure that the prediction of fin performances is approximated by choosing a linear relationship between specific humidity and film temperature may be exhibited near to the exact value for a lower value of relative humidity, otherwise the linear model provides a crude approximating analysis for estimating fin performances. The dry length in partially wet fins is also calculated for the aforementioned design condition and it is depicted in Fig. 5 as a function of relative humidity. In this case also, the existing analytical model for partially wet fins is agreed satisfactorily with the present model and the numerical works.

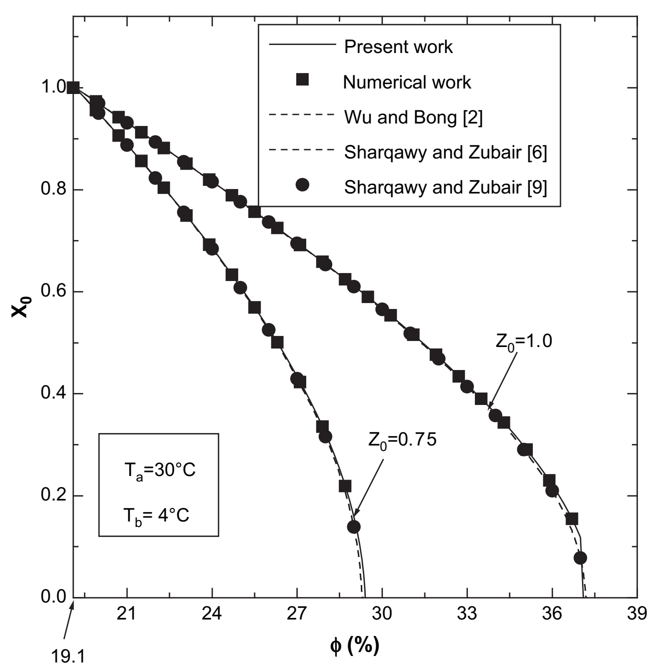

Fig. 5. Dry length X_0 for a partially wet fin as a function of relative humidity estimated by present and previous methods under the same design condition.

Fig. 6 depicts the variation of fin performances of wet fins as a function of fin parameter Z_0 by different methods of forecast. From the figure, it is clear that for a given ambient temperature and base temperature, the fin surface may be in fully wet or in partially wet, depends mainly upon the parameter, Z_0 and relative humidity of the air. For a lower value of Z_0, a fully wet surface is found even though the relative humidity of the surrounding air is sufficiently low. On the other hand for a higher value of Z_0, the fin surface is either in fully wet or in partially wet depending exclusively upon the relative humidity of the surrounding air. It can be demonstrated once again from the figure that the fin performances predicted by the present model is less responsive with the relative humidity in comparison with that by the previous linear model [6]. It can be mentioned once more from the figure that for a lower value of relative humidity, fin performances estimated by the previous models [2,6] give almost the same value with the present model.

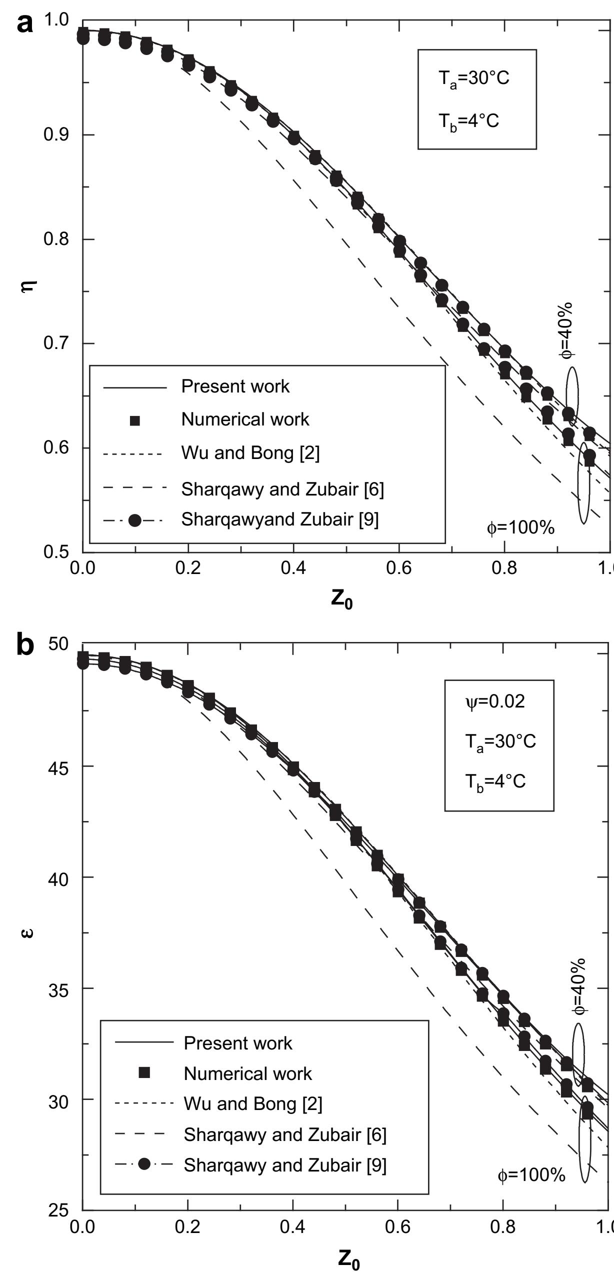

Fig. 6. Comparison of present and published results of fin performances for wet fins as a function of Z_0 and relative humidity: (a) Fin efficiency; (b) Fin effectiveness.

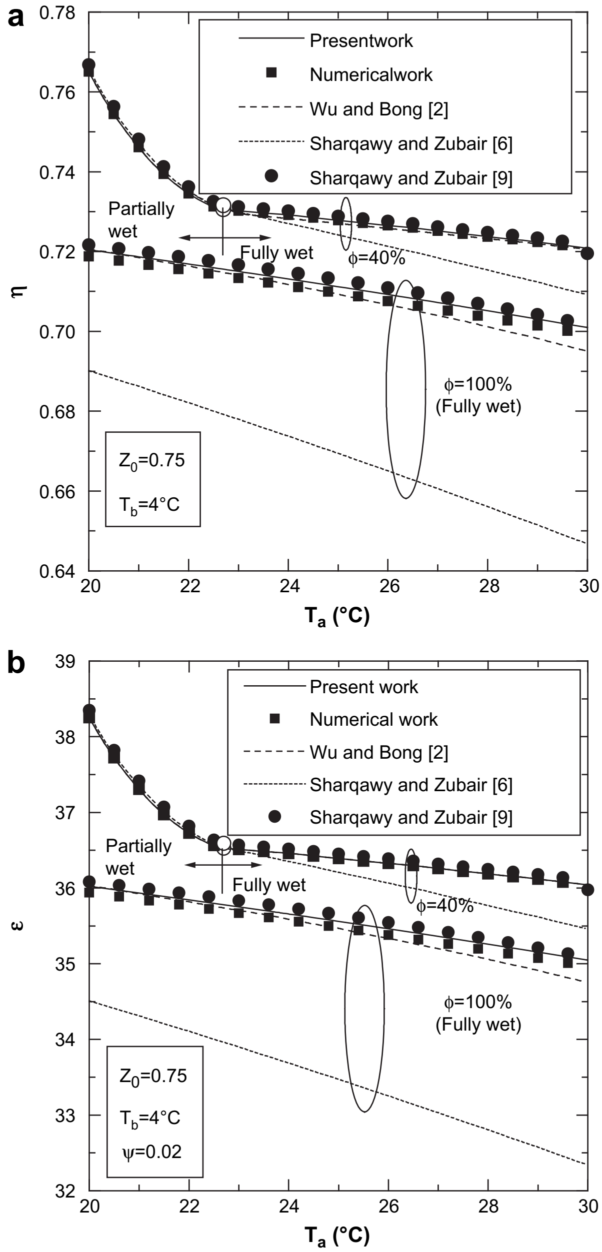

Fig. 7. Comparison of present and published results of fin efficiency for fully wet fins as a function of relative humidity and DBT: (a) fin efficiency; (b) fin effectiveness.

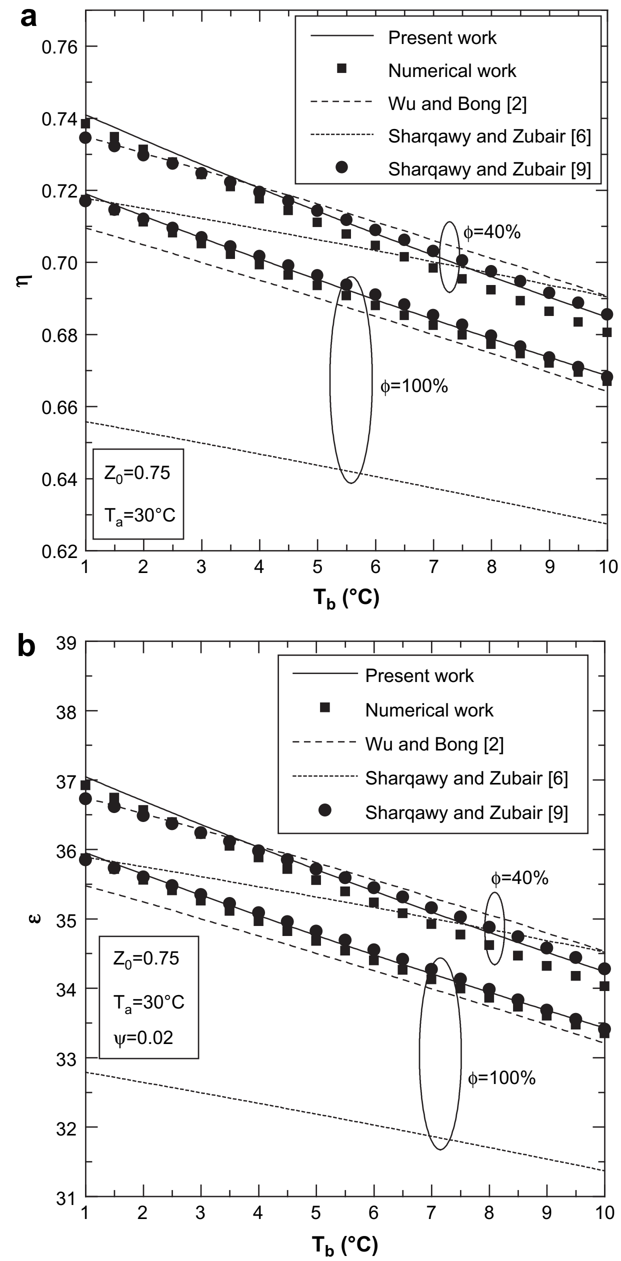

Fig. 8. Comparison of present and published results of fin performances for wet fins as a function of relative humidity and fin base temperature: (a) fin efficiency; (b) fin effectiveness.

For all range of variables considered in this figure, the numerical results (both present and Sharqawy and Zubair [9]) are matched satisfactorily with that of the present model. Therefore, it may be concluded that the error of results by assuming a linear relation between specific humidity and fin surface temperature cannot be neglected for high values of relative humidity.

Most of the previous works have been concentrated for determination of performance parameters of wet fins through analytical solutions based on the linear relationship between specific humidity and fin surface temperature. It was already established that this assumption may be suitable for a differential range of temperature difference between fin tip and fin base. The fin tip temperature depends upon the relative humidity of air, ambient temperature and fin parameter Z_0 as well as fin base temperature also. For a design application, fin base temperature is taken a constant and thus tip temperature is a function of other parameters mentioned in the above. The effect of fin parameter Z_0 and relative humidity on the fin performance has already been examined in this study. On the other hand, in the refrigeration and air conditioning equipments, the dehumidification of air on the fin surface takes place only when the fin surface temperature is below the dewpoint temperature of the surrounding. The value of dewpoint temperature is dependent upon the ambient temperature for a constant relative humidity. Generally, the ambient temperature varies considerably day to day or even in a day and thus in this section, an exercise has been made for the variation of fin performance as a function of ambient temperature which is shown in Fig. 7. The fin performance of wet fins decreases with the increase in ambient temperature because of increase in condensation of moisture on the fin surface. In partially wet fins, this effect shows more in comparison with the fully wet fin. The different methods of prediction for the same design variables are also plotted in this figure. The results obtained from the numerical schemes give very closer to that from the present analysis for all values of ambient temperature considered in this study. However, difference in results predicted by present model and published models [2,6] is occurred particularly in fully wet fins and it is shown an incremental function with the ambient temperature. A significant difference is found when present result is compared with that from the Sharqawy and Zubair analysis [6].

The fin base temperature is a design parameter which is generally kept at a constant value for practical applications. However for different purposes, its value is different. Thus in this paragraph, a theoretical study has been made for the variation of fin performances of wet fins with the fin base temperature. Fig. 8 depicts the fin performance as a function of base temperature and relative humidity. In every different constant values of relative humidity, the fin performance declines with the fin base temperature. A comparison of different methods of prediction is also done in this figure for the aforementioned design variation. Again numerical results give a closer prediction to the values obtained from the present approximate analytical analysis. However, the accuracy level of published model is also a dependent function with the design variable selected. At a high value of fin base temperature, reasonable matching of results may be obtained.

4. Conclusions

For the establishment of an analytical solution of fins subjected to combined heat and mass transfer, exercises had already been made by many researches for determining the overall fin performances by approximating a linear relation between specific humidity and the saturation temperature. However, it can be mentioned from the psychrometric properties of air that this linear relation never exists in the actual correlation. In the present study, the analysis of wet fins is carried out by an approximate analytical technique with considering a cubic polynomial relation between the above variables and this relation is determined by the regression analysis using the psychrometric data. This cubic function is used to calculate the mass transfer for the analysis of overall fin performances by applying the ADM when operating under fully wet and partially wet conditions. The following concluding remarks may be drawn from the present study:

1. A model has been established for determination of fin performances of wet fins which treated the mass transfer in a better way in comparison with the published linear models [2,6]. A new analytical scheme has been demonstrated for the analysis of partially wet fins.
2. The present result is compared with the existing literature results [2,6,9] and a difference in results is noticed when it is compared with those from the linear models [2,6]. Thus the superiority of the present model is identified.
3. The fin surface whether it is dry, partially wet or fully wet, the main deciding factors are relative humidity and fin parameter Z_0.
4. The fin performances from the present model are of comparable magnitude with that from the published papers [2,6] for the dry surface or partially wet surface conditions. However for the fully wet surface, deviation of these results is noticed significantly for a higher value of relative humidity for a constant Z_0. The maximum deviation is noticed for the 100% relative humidity.
5. For the fully wet fin, the overall fin performance of the present model shows an insignificant variation with the relative humidity. However, a noteworthy change of this variation was found in the published linear model [6].
6. The overall performance of wet fins decreases with the increase in ambient temperature, fin base temperature or both ambient and fin base temperatures, separately.
7. The linear approximate model may predict results satisfactorily for a smaller range of temperature difference from the fin base to fin tip and also for a lower value of relative humidity of the surrounding air.
8. As the analysis is a closed form approximate analytical model, the proposed model, thus, can be extended easily to the fin optimization problems with the help of the classical minimization technique.

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